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IFAC PapersOnLine 50-1 (2017) 12458–12463

A Framework for the Simulation and Validation of Distributed Control Architectures for Technical Systems of Systems ⋆

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Abstract: There are many examples of modern technical systems that consist of many closely integrated physical and cyber subsystems. Centralized management and control strategies may not always be the best option, or may even be infeasible, for these so-called *cyber-physical systems of systems* (CPSoS) due to their large complexity or due to confidentiality restrictions between the subsystems. These challenges can be overcome by distributed management and coordination strategies that do not require a central controller. Instead, each subsystem solves its own local optimization problem and only reports limited information to a higher-level controller to ensure the satisfaction of the global constraints which are often defined as limitations on the utilization or production on some shared resources or raw materials. This paper presents a novel *Modelica*-based software framework that supports the development of such distributed management and control systems by providing a structured, plug-and-play approach for the validation of distributed management architectures on simulation models of the controlled CPSoS, and for the subsequent deployment into operational environments. The capabilities of the framework are demonstrated on two complex, industrial use cases, the distributed management of an integrated chemical production site and the distributed optimization of a network of multi-product semi-batch reactors.

Keywords: Distributed management, distributed control, simulation, model-based validation, *Modelica*, integrated petrochemical production site, semi-batch reactor network

1. INTRODUCTION

Many of today's large-scale technical systems, such as electrical power networks, industrial production complexes, or transportation networks, consist of many, partly autonomous physical and computing components that are closely integrated and exhibit complex interactions. Although a plant-wide, centralized optimal management and coordination strategy for such *cyber-physical systems of systems* (*CPSoS*, Engell et al. (2016)) will often lead to efficient operation, it is not always feasible or desired due to the large complexity of the overall coordination problem or due to confidentiality concerns of the individual subsystems that may arise from privacy concerns that prohibit the sharing of operational details. An example is a chemical production complex where plants are operated by different business units or different companies, each of which tries to maximize their own profit while not disclosing information about the production process to other units for competitive reasons.

Thus, distributed management, coordination, and optimization approaches are often preferred for these systems. In distributed approaches, such as the price-based coordination methodologies that are considered in this paper, each subsystem aims at optimizing its own performance while a high-level coordinator influences the decisions of the subsystems via a suitable incentive, such as varying internal prices that are assigned to the use of shared resources (e.g. raw material, cooling capacity, etc.), with the goal to drive the behaviour of the overall system towards the global optimum. By the iterative adaptation of the prices, the coordinator drives the subsystems to modify their resource production/consumption until global constraints (that e.g. enforce an equilibrium of the demand and supply of the shared resources) are satisfied. Thus, distributed management, coordination, and optimization approaches are often preferred for these systems. In distributed approaches, such as the price-based coordination

⋆ The authors acknowledge the support of the European Commission under the grant agreement number 611281 (FP7 ICT project DYMASOS).

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Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.1921

methodologies that are considered in this paper, each subsystem aims at optimizing its own performance while a high-level coordinator influences the decisions of the subsystems via a suitable incentive, such as varying internal prices that are assigned to the use of shared resources (e.g. raw material, cooling capacity, etc.), with the goal to drive the behaviour of the overall system towards the global optimum. By the iterative adaptation of the prices, the coordinator drives the subsystems to modify their resource production/consumption until global constraints (that e.g. enforce an equilibrium of the demand and supply of the shared resources) are satisfied.

Because of their large potential to provide significant efficiency gains for large-scale technical systems that are too complex for centralized optimization, and because these methods only require limited exchange of information between different subsystems, novel distributed management and coordination methods and tools are in the focus of several research and innovation efforts [1], but bridging the gap between academic research and development and industrial deployment is a major challenge. Academic prototypes are often implemented in a proprietary fashion, which makes it difficult to connect them to (often pre-existing, heterogeneous) simulation models since suitable interfaces and integrations must be built manually. For the systematic validation of such novel solutions, a plug-and-play approach is needed that allows engineers to quickly assemble a simulation model of a complex CPS from model components, to implement the often complex communication architecture of the distributed architecture, to integrate distributed management architectures with simulation models, and to quickly modify simulation models such that they reflect the constant evolution of the CPS that is always present as the engineering of these systems is never finished (e.g. due to inclusion of new components, decommissioning of old components, or replacement of components due to malfunctions or modernization).

In this paper, a simulation and validation framework (SVF) is presented [2] that addresses these challenges. The framework, which is based on the object-oriented, equation-based and open modeling language *Modelica* for heterogeneous modeling, see e.g. Fritzson (2015), provides a structured approach for the implementation of large-scale CPSoS models and their connection to distributed automation architectures that aims at reducing the (currently large) engineering effort while improving the quality of the designed system. An essential feature of the framework is that it provides standardized and generic interfaces to which management algorithms and different types of models can be easily connected. Standardized interfaces allow engineers to extend the distributed management systems, which will significantly increase the re-usability of newly developed models in different scenarios, makes the model development more efficient and less error-prone, and allows to easily test and validate different management algorithms on an (existing) model of an industrial CPSoS. They also simplify the deployment of new distributed management architectures to the automation hardware of the real-world CPSoS since the interfaces can be directly connected to hardware systems.

[1] See e.g. http://www.dymasos.eu/

[2] A preliminary version of this framework is described in Nazari et al. (2015a).

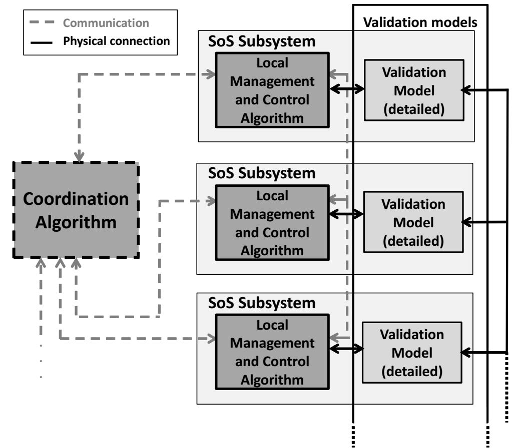

Fig. 1. The conceptual structure of the simulation and validation framework.

The remainder of this paper is structured as follows: In section 2, the simulation and validation framework is described. The capabilities of the framework are subsequently illustrated on two realistic use cases, an integrated chemical production complex and a multi-reactor multi-product semi-batch plant, in sections 3 and 4. The paper closes with conclusions in section 5.

2. THE SIMULATION AND VALIDATION FRAMEWORK

A conceptual outline of the simulation and validation framework is shown in Fig. 1. Each subsystem (representing a physical component of the overall system, such as a processing plant) in this framework is assumed to include a *local management and control algorithm* which performs real-time control. The behavior of each subsystem is represented by a *validation model* (a detailed model of the physical system) and is connected to the local control algorithm via standardized interfaces. The interfaces are indicated in Fig. 1 using solid and dashed arrows. If a hierarchical management system is desired, an additional global *coordination algorithm* can be connected to the local controllers.

The simulation and validation framework is implemented as a generic *Modelica*-based component that includes five *Modelica*-based packages, each of which implements a major part of the framework, and the simulation model of a CPSoS is a custom *Modelica* model that relies on the features and structures that are defined in these packages, such as a generic *Model Management Engine(MME)* that is responsible for orchestrating the executions of the system components and for transferring data between between the components.

The simulation model of a CPSoS does not have to be generated manually by the user. Instead, a generic, easy-to-understand XML-based configuration file has been developed that serves as an input for the generation of the simulation model in *Modelica*, including all the interconnections, components, and interfaces, see Nazari et al. (2015b). The simulation model is generated by parsing the